# EXHIBIT 18

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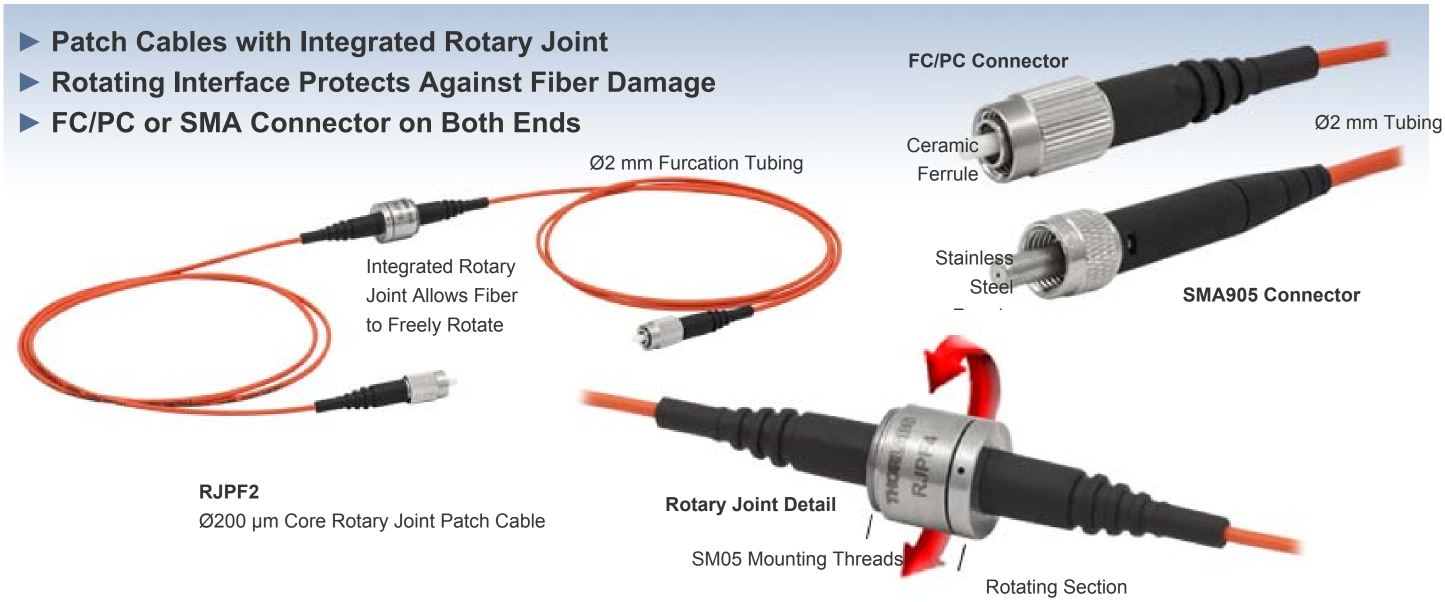
THORLABS

# MULTIMODE FIBER OPTIC ROTARY JOINT PATCH CABLES



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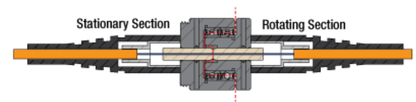
OVERVIEW

### Features

- Articulated Rotary Joint Protects Against Fiber Damage Caused by Twisting Motion
- Ø200 µm or Ø400 µm Core Multimode Fiber
- Available with SMA905 or FC/PC (2.0 mm Narrow Key) Connectors
- Custom Cables are Available by Request
- Extremely Smooth Rotation
- SM05-Threaded (0.535"-40) Rotary Joint for Secure Mounting

Click to Enlarge
The External SM05 Threading on the Rotary Joint Allows for Compatibility with Our Line of SM05-Threaded Optic Mounts, such as the LMR05 Lens Mount Shown Here.

Thorlabs' Multimode (MM) Fiber Optic Rotating Patch Cables are one-piece solutions for experiments that involve rotating one end of a cable. The built-in rotary joint allows one end to freely rotate while keeping the other end stationary. The lens-free design also provides lower insertion loss and less rotational transmission variation than a separate rotary joint and patch cables solution.




Click to Enlarge
The Rotary Joint Uses a Butt-Coupled Design with Two Fiber Ferrules in Close Proximity to Yield Low Insertion Loss

The rotary joint is precision machined and has sealed bearings for extremely smooth rotation, long lifetime, and low signal strength variations as the joint rotates. The rotary joint features an external SM05 (0.535"-40) mounting thread for compatibility with our Ø1/2" optic mounts.

These cables incorporate FT200EMT Ø200 µm core or FT400EMT Ø400 µm core, 0.39 NA fiber. To each side of the rotary joint, there is 1 m of fiber with standard FT020 orange tubing that has been terminated with either an FC/PC or SMA connector. Each rotary joint patch cable includes two protective caps that shield the ferrule ends from dust and other hazards. Additional CAPM rubber or CAPMM metal caps for SMA connectors and CAPF plastic or CAPFM metal caps for FC/PC connectors are sold separately. Compared to unterminated fiber, the maximum power of these cables is limited due to their connectorization. Please see the *Damage Threshold* tab for detailed information.

**Optogenetics**
We also offer rotary joint patch cables for optogenetics. They are commonly used in this field because of their ease of use with moving specimens. These cables differ in that they have a lightweight black tubing with a low-profile ferrule for cannula interconnection on the specimen-side of the rotary joint. They provide a complete solution for connecting the light source to an implanted fiber optic cannula and are compatible with all Thorlabs light sources and optogenetics equipment. Thorlabs offers a full line of optogenetics equipment for *in vivo* stimulation, including: implantable fiber optic cannulae, fiber optic patch cables and rotary joint patch cables for Optogenetics, Fiber-Coupled LEDs, and a multimode laser light source. For more information on our selection of optogenetics equipment please see our Optogenetics Overview.

## Custom Rotary Joint Cables

The fiber leads of these cables are permanently attached to the rotary joint for higher performance and provide a one piece, integrated fiber optic solution. For compatibility with a wide range of experimental setups, we can produce custom rotary joint cables using fibers with different core sizes and NAs. We can also produce cables with different connectors or any length of fiber on each end of the joint. For best performance, the fiber core size should be 200 µm or greater. Contact Tech Support to order a custom rotary joint cable.

<table>
<tr><th colspan="7">In-Stock Multimode Fiber Optic Patch Cable Selection</th></tr>
<tr><th colspan="5">Step Index</th><th rowspan="2">Graded Index</th><th rowspan="3">Fiber Bundles</th></tr>
<tr><th>Uncoated</th><th>Coated</th><th>Mid-IR</th><th>Optogenetics</th><th>Specialized Applications</th></tr>
<tr><td>SMA<br>FC/PC<br>FC/PC to SMA<br>Square-Core FC/PC and SMA</td><td>AR-Coated SMA<br>HR-Coated FC/PC<br>Beamsplitter-Coated FC/PC</td><td>Fluoride FC and SMA</td><td>Lightweight FC/PC<br>Lightweight SMA<br>Rotary Joint FC/PC and SMA</td><td>High-Power SMA<br>Vacuum-Compatible SMA<br>Armored SMA<br>Solarization-Resistant SMA</td><td>FC/PC</td></tr>
</table>

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SPECS

| Specifications | | | | |
|---|---|---|---|---|
| **Item #** | **RJPS2** | **RJPF2** | **RJPS4** | **RJPF4** |
| Connector Type | SMA (10230A[a]) | FC/PC (30230C1[b]) | SMA (10440A[a]) | FC/PC (30440C1[b]) |
| Fiber Type | FT200EMT | | FT400EMT | |
| Fiber Core Size | Ø200 µm | | Ø400 µm | |
| Fiber NA | 0.39 | | | |
| Wavelength Range | 400 - 2200 nm | | | |
| Length | 1 m on Both Sides of Rotary Joint | | | |
| Fiber Jacket | Ø2 mm, Orange (FT020) | | | |
| **Rotary Joint Specifications** | | | | |
| Insertion Loss Through Rotary Joint | <2.0 dB (Transmission >63%) | | | |
| Variation in Insertion Loss During Rotation | ±0.4 dB (Transmission ±8%) | | | |
| Start-Up Torque | <0.01 N•m | | | |
| RPM (Max)[c] | 10,000 | | | |
| Lifetime Cycle | 200 - 400 Million Revolutions | | | |
| Operating Temperature | <50 °C | | | |

- Connectorized with the 190088CP strain relief boot for Ø2 mm tubing
- Connectorized with the 190066CP strain relief boot for Ø2 mm tubing
- Tested for the bearings in the rotary joint segment

## Fiber Specs

| Item # | Fiber Type | NA | Core / Cladding | Core Diameter | Cladding Diameter | Coating Diameter | Max Core Offset | Bend Radius (Short Term / Long Term) |
|---|---|---|---|---|---|---|---|---|
| RJPF2 and RJPS2 | FT200EMT | 0.39 | Pure Silica / TECS Hard Cladding | 200 ± 5 µm | 225 ± 5 µm | 500 ± 30 µm | 5 µm | 9 mm / 18 mm |
| RJPF4 and RJPS4 | FT400EMT | | | 400 ± 8 µm | 425 ± 10 µm | 730 ± 30 µm | 7 µm | 20 mm / 40 mm |

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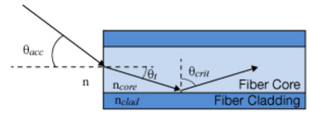
MM FIBER TUTORIAL

## Guiding Light in an Optical Fiber

Optical fibers are part of a broader class of optical components known as waveguides that utilize total internal reflection (TIR) in order to confine and guide light within a solid or liquid structure. Optical fibers, in particular, are used in numerous applications; common examples include telecommunications, spectroscopy, illumination, and sensors.



Click to Enlarge
Total Internal Reflection in an Optical Fiber

One of the more common glass (silica) optical fibers uses a structure known as a step-index fiber, which is shown in the image to the right. Step-index fibers have an inner core made from a material with a refractive index that is higher than the surrounding cladding layer. Within the fiber, a critical angle of incidence exists such that light will reflect off the core/cladding interface rather than refract into the surrounding medium. To fulfill the conditions for TIR in the fiber, the angle of incidence of light launched into the fiber must be less than a certain angle, which is defined as the acceptance angle, $\theta_{acc}$. Snell's law can be used to calculate this angle:

$$\sin\theta_{crit} = \frac{n_{clad}}{n_{core}} = \cos\theta_t$$

$$n\sin\theta_{acc} = n_{core}\sqrt{1-\cos^2\theta_t} = \sqrt{n_{core}^2 - n_{clad}^2}$$

where $n_{core}$ is the refractive index of the fiber core, $n_{clad}$ is the refractive index of the fiber cladding, n is the refractive index of the outside medium, $\theta_{crit}$ is the critical angle, and $\theta_{acc}$ is the acceptance half-angle of the fiber. The numerical aperture (NA) is a dimensionless quantity used by fiber manufacturers to specify the acceptance angle of an optical fiber and is defined as:

$$NA = n\sin\theta_{acc} = \sqrt{n_{core}^2 - n_{clad}^2}$$

In step-index fibers with a large core (multimode), the NA can be calculated directly using this equation. The NA can also be determined experimentally by tracing the far-field beam profile and measuring the angle between the center of the beam and the point at which the beam intensity is 5% of the maximum; however, calculating the NA directly provides the most accurate value.

## Number of Modes in an Optical Fiber

Each potential path that light propagates through in an optical fiber is known as a guided mode of the fiber. Depending on the physical dimensions of the core/cladding regions, refractive index, and wavelength, anything from one to thousands of modes can be supported within a single optical fiber. The two most commonly manufactured variants are single mode fiber (which supports a single guided mode) and multimode fiber (which supports a large number of guided modes). In a multimode fiber, lower-order modes tend to confine light spatially in the core of the fiber; higher-order modes, on the other hand, tend to confine light spatially near the core/cladding interface.

Using a few simple calculations, it is possible to estimate the number of modes (single mode or multimode) supported by an optical fiber. The normalized optical frequency, also known as the V-number, is a dimensionless quantity that is proportional to the free space optical frequency but is normalized to guiding properties of an optical fiber. The V-number is defined as:

$$V = \frac{2\pi a}{\lambda} NA$$

where V is the normalized frequency (V-number), a is the fiber core radius, and λ is the free space wavelength. Multimode fibers have very large V-numbers; for example, a Ø50 µm core, 0.39 NA multimode fiber at a wavelength of 1.5 µm has a V-number of 40.8.

For multimode fiber, which has a large V-number, the number of modes supported is approximated using the following relationship.

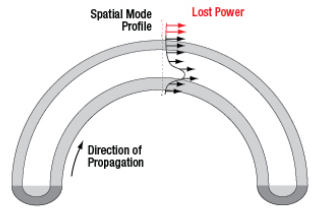
$$M \approx \frac{V^2}{2}$$

In the example above of the Ø50 µm core, 0.39 NA multimode fiber, it supports approximately 832 different guided modes that can all travel simultaneously through the fiber.

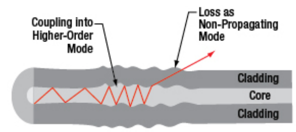
Single mode fibers are defined with a V-number cut-off of V < 2.405, which represents the point at which light is coupled only into the fiber's fundamental mode. To meet this condition, a single mode fiber has a much smaller core size and NA compared to a multimode fiber at the same wavelength. One example of this, SMF-28 Ultra single mode fiber, has a nominal NA of 0.14 and an Ø8.2 µm core at 1550 nm, which results in a V-number of 2.404.

## Sources of Attenuation

Loss within an optical fiber, also referred to as attenuation, is characterized and quantified in order to predict the total transmitted power lost within a fiber optic setup. The sources of these losses are typically wavelength dependent and range from the material used in the fiber itself to bending of the fiber. Common sources of attenuation are detailed below:




Click to Enlarge
Attenuation Due to Macrobend Loss

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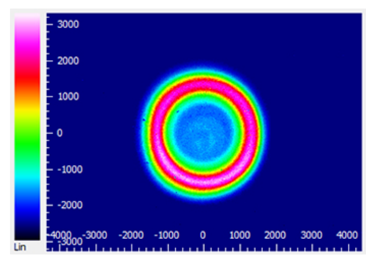
Attenuation Due to Microbend Loss

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Beam profile measurement of FT200EMT multimode fiber and a former generation M565F1 LED (replaced by the M565F3) showing light guided in the cladding rather than the core of the fiber.

### Absorption

Because light in a standard optical fiber is guided via a solid material, there are losses due to absorption as light propagates through the fiber. Standard fibers are manufactured using fused silica and are optimized for transmission from 1300 nm to 1550 nm. At longer wavelengths (>2000 nm), multi-phonon interactions in fused silica cause significant absorption. Fluoride glasses such as $ZrF_4$ and $InF_3$ are used in manufacturing Mid-IR optical fibers primarily because they exhibit lower loss at these wavelengths. $ZrF_4$ and $InF_3$ fibers have a multi-phonon edge of ~3.6 µm and ~4.6 µm, respectively.

Contaminants in the fiber also contribute to the absorption loss. One example of an undesired impurity is water molecules that are trapped in the glass of the optical fiber, which will absorb light around 1300 nm and 2.94 µm. Since telecom signals and some lasers operate in that same region, any water molecules present in the fiber will attenuate the signal significantly.

The concentration of ions in the fiber glass is often controlled by manufacturers to tune the transmission/attenuation properties of a fiber. For example, hydroxyl ions (OH-) are naturally present in silica and absorb light in the NIR-IR spectrum. Therefore, fibers with low-OH content are preferred for transmission at telecom wavelengths. On the other hand, fibers with high-OH content typically exhibit increased transmission at UV wavelengths and thus may be preferred by users interested in applications such as fluorescence or UV-VIS spectroscopy.

### Scattering

For the majority of fiber optics applications, light scattering is a source of loss that occurs when light encounters a change in the refractive index of the medium. These changes can be extrinsic, caused by impurities, particulates, or bubbles; or intrinsic, caused by fluctuations in the glass density, composition, or phase state. Scattering is inversely related to the wavelength of light, so scattering loss becomes significant at shorter wavelengths such as the UV or blue regions of the spectrum. Using proper fiber cleaning, handling, and storage procedures may minimize the presence of impurities on tips of fibers that cause large scattering losses.

### Bending Loss

Losses that occur due to changes in the external and internal geometry of an optical fiber are known as bending loss. These are usually separated into two categories: macrobending loss and microbending loss.

Macrobend loss is typically associated with the physical bending of an optical fiber; for example, rolling it in a tight coil. As shown in the image to the right, guided light is spatially distributed within the core and cladding regions of the fiber. When a fiber is bent at a radius, light near the outer radius of the bend cannot maintain the same spatial mode profile without exceeding the speed of light. Instead, the energy is lost to the surroundings as radiation. For a large bend radius, the losses associated with bending are small; however, at bend radii smaller than the recommended bend radius of a fiber, bend losses become very significant. For short periods of time, optical fibers can be operated at a small bend radius; however, for long-term storage, the bend radius should be larger than the recommended value. Use proper storage conditions (temperature and bend radius) to reduce the likelihood of permanently damaging the fiber; the FSR1 Fiber Storage Reel is designed to minimize high bend loss.

Microbend loss arises from changes in the internal geometry of the fiber, particularly the core and cladding layers. These random variations (i.e., bumps) in the fiber structure disturb the conditions needed for total internal reflection, causing propagating light to couple into a non-propagating mode that leaks from the fiber (see the image to the right for details). Unlike macrobend loss, which is controlled by the bend radius, microbend loss occurs due to permanent defects in the fiber that are created during fiber manufacturing.

### Cladding Modes

While most light in a multimode fiber is guided via TIR within the core of the fiber, higher-order modes that guide light within both the core and cladding layer, because of TIR at the cladding and coating/buffer interface, can also exist. This results in what is known as a cladding mode. An example of this can be seen in the beam profile measurement to the right, which shows cladding modes with a higher intensity in the cladding than in the core of the fiber. These modes can be non-propagating (i.e., they do not fulfill the conditions for TIR) or they can propagate over a significant length of fiber. Because cladding modes are typically higher-order, they are a source of loss in the presence of fiber bending and microbending defects. Cladding modes are also lost when connecting two fibers via connectors as they cannot be easily coupled between optical fibers.

Cladding modes may be undesired for some applications (e.g., launching into free space) because of their effect on the beam spatial profile. Over long fiber lengths, these modes will naturally attenuate. For short fiber lengths (<10 m), one method for removing cladding modes from a fiber is to use a mandrel wrap at a radius that removes cladding modes while keeping the desired propagating modes.

## Launch Conditions

**Underfilled Launch Condition**

For a large multimode fiber which accepts light over a wide NA, the condition of the light (e.g., source type, beam diameter, NA) coupled into the fiber can have a significant effect on performance. An underfilled launch condition occurs when the beam diameter and NA of light at the coupling interface are smaller than the core diameter and NA of the fiber. A common example of this is launching a laser source into a large multimode fiber. As seen in the diagram and beam profile measurement below, underfilled launches tend to concentrate light spatially in the center of the fiber, filling lower-order modes preferentially over higher-order modes. As a result, they are less sensitive to macrobend losses and do not have cladding modes. The measured insertion loss for an underfilled launch tends to be lower than typical, with a higher power density in the core of the fiber.


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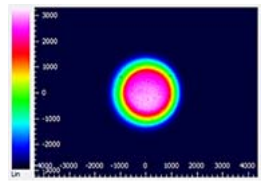

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Diagram illustrating an underfilled launch condition (left) and a beam profile measurement using a FT200EMT multimode fiber (right).

**Overfilled Launch Condition**

Overfilled launches are defined by situations where the beam diameter and NA at the coupling interface are larger than the core diameter and NA of the fiber. One method to achieve this is by launching light from an LED source into a small multimode fiber. An overfilled launch completely exposes the fiber core and some of the cladding to light, enabling the filling of lower- and higher-order modes equally (as seen in the images below) and increasing the likelihood of coupling into cladding modes of the fiber. This increased percentage of higher-order modes means that overfilled fibers are more sensitive to bending loss. The measured insertion loss for an overfilled launch tends to be higher than typical, but results in an overall higher output power compared to an underfilled fiber launch.


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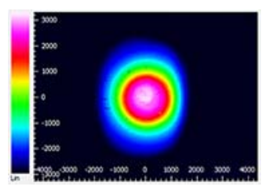

Click to Enlarge

Diagram illustrating an overfilled launch condition (left) and a beam profile measurement using a FT200EMT multimode fiber (right).

There are advantages and disadvantages to underfilled or overfilled launch conditions, depending on the needs of the intended application. For measuring the baseline performance of a multimode fiber, Thorlabs recommends using a launch condition where the beam diameter is 70-80% of the fiber core diameter. Over short distances, an overfilled fiber has more output power; however, over long distances (>10 - 20 m) the higher-order modes that more susceptible to attenuation will disappear.

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DAMAGE THRESHOLD

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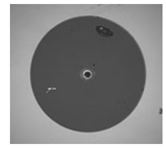
## Laser Induced Damage in Silica Optical Fibers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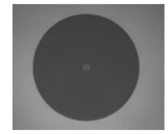
Damaged Fiber End


Click to Enlarge
Undamaged Fiber End

The following tutorial details damage mechanisms in unterminated (bare) and terminated optical fibers, including damage mechanisms at both the air-to-glass interface and within the glass of the optical fiber. Please note that while general rules and scaling relations can be defined, absolute damage thresholds in optical fibers are extremely application dependent and user specific. This tutorial should only be used as a guide to estimate the damage threshold of an optical fiber in a given application. Additionally, all calculations below only apply if all cleaning and use recommendations listed in the last section of this tutorial have been followed. For further discussion about an optical fiber's power handling abilities within a specific application, contact Thorlabs' Tech Support.

## Damage at the Free Space-to-Fiber Interface

There are several potential damage mechanisms that can occur at the free space-to-fiber interface when coupling light into a fiber. These come into play whether the fiber is used bare or terminated in a connector.

### Unterminated (Bare) Fiber

Damage mechanisms in bare optical fiber can be modeled similarly to bulk optics, and industry-standard damage thresholds for UV Fused Silica substrates can be applied to silica-based fiber (refer to the table to the right). The surface areas and beam diameters involved at the air-to-glass interface are extremely small compared to bulk optics, especially with single mode (SM) fiber, resulting in very small damage thresholds.

| Unterminated Silica Fiber Maximum Power Densities | | |
|---|---|---|
| **Type** | **Theoretical Damage Threshold** | **Practical Safe Value** |
| CW (Average Power) | 1 MW/cm$^2$ | 250 kW/cm$^2$ |
| 10 ns Pulsed (Peak Power) | 5 GW/cm$^2$ | 1 GW/cm$^2$ |

The effective area for SM fiber is defined by the mode field diameter (MFD), which is the effective cross-sectional area through which light propagates in the fiber. To achieve good efficiency when coupling into a single mode fiber, a free-space beam of light must match the diameter given by the MDF. Thus, a portion of the light travels through the cladding when matching the MFD. The MFD increases roughly linearly with wavelength, which yields a roughly quadratic increase in damage threshold with wavelength. Additionally, a beam coupled into SM fiber typically has a Gaussian-like profile, resulting in a higher power density at the center of the beam compared with the edges, so a safety margin must be built into the calculated damage threshold value if the calculations assume a uniform density.

Multimode (MM) fiber's effective area is defined by the core diameter, which is typically far larger than the MFD in SM fiber. Kilowatts of power can be typically coupled into multimode fiber without damage, due to the larger core size and the resulting reduced power density. For MM fibers, a free-space beam of light must be focused down to a spot of roughly 70 - 80% of the MFD to be coupled into the fiber with good efficiency.

It is typically uncommon to use single mode fibers for pulsed applications with high per-pulse powers because the beam needs to be focused down to a very small area for coupling, resulting in a very high power density. It is also uncommon to use SM fiber with ultraviolet light because the MFD becomes extremely small; thus, power handling becomes very low, and coupling becomes very difficult.

**Example Calculation**

For SM400 single mode fiber operating at 400 nm with CW light, the mode field diameter (MFD) is approximately Ø3 µm. For good coupling efficiency, the light must fill the MFD of the fiber. Thus, the effective diameter is Ø3 µm with an effective area of 7.07 µm$^2$:

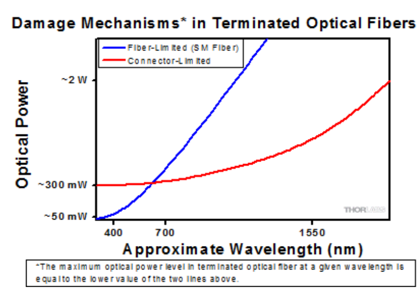
$$\text{Area} = \pi r^2 = \pi(\text{MFD}/2)^2 = \pi \cdot 1.5^2\ \mu m^2 = 7.07\ \mu m^2$$

This can be extrapolated to a damage threshold of 17.7 mW. We recommend using the "practical value" maximum power density from the table above to account for a Gaussian power distribution, possible coupling misalignment, and contaminants or imperfections on the fiber end face:

$$250\ kW/cm^2 = 2.5\ mW/\mu m^2$$

$$7.07\ \mu m^2 \cdot 2.5\ mW/\mu m^2 = 17.7\ mW$$

### Terminated Fiber



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Optical fiber that is terminated in a connector has additional power handling considerations. Fiber is typically terminated by being epoxied into a ceramic or steel ferrule, which forms the interfacing surface of the connector. When light is coupled into the fiber, light that does not enter the core and propagate down the fiber is scattered into the outer layers of the fiber, inside the ferrule.

The scattered light propagates into the epoxy that holds the fiber in the ferrule. If the light is intense enough, it can melt the epoxy, causing it to run onto the face of the connector and into the beam path. The epoxy can be burned off, leaving residue on the end of the fiber, which

reduces coupling efficiency and increases scattering, causing further damage. The lack of epoxy between the fiber and ferrule can also cause the fiber to be decentered, which reduces the coupling efficiency and further increases scattering and damage.

The limiting factor with optical fiber terminated in a connector is free-space light entering the fiber.

The power handling of terminated optical fiber scales with wavelength for two reasons. First, the higher per photon energy of short-wavelength light leads to a greater likelihood of scattering, which increases the optical power incident on the epoxy near the end of the connector. Second, shorter-wavelength light is inherently more difficult to couple into SM fiber due to the smaller MFD, as discussed above. The greater likelihood of light not entering the fiber's core again increases the chance of damaging scattering effects. This second effect is not as common with MM fibers because their larger core sizes allow easier coupling in general, including with short-wavelength light.

Fiber connectors can be constructed to have an epoxy-free air gap between the optical fiber and ferrule near the fiber end face. This design feature, commonly used with multimode fiber, allows some of the connector-related damage mechanisms to be avoided. Our high-power multimode fiber patch cables use connectors with this design feature.

**Combined Damage Thresholds**

As a general guideline, for short-wavelength light at around 400 nm, scattering within connectors typically limits the power handling of optical fiber to about 300 mW. Note that this limit is higher than the limit set by the optical power density at the fiber tip. However, power handing limitations due to connector effects do not diminish as rapidly with wavelength when compared to power density effects. Thus, a terminated fiber's power handling is "connector-limited" at wavelengths above approximately 600 nm and is "fiber-limited" at lower wavelengths.

The graph to the right shows the power handling limitations imposed by the fiber itself and a surrounding connector. The total power handling of a terminated fiber at a given wavelength is limited by the lower of the two limitations at that wavelength. The fiber-limited (blue) line is for SM fibers. An equivalent line for multimode fiber would be far above the SM line on the Y-axis. For terminated multimode fibers, the connector-limited (red) line always determines the damage threshold.

Please note that the values in this graph are rough guidelines detailing estimates of power levels where damage is very unlikely with proper handling and alignment procedures. It is worth noting that optical fibers are frequently used at power levels above those described here. However, damage is likely in these applications. The optical fiber should be considered a consumable lab supply if used at power levels above those recommended by Thorlabs.

## Damage Within Optical Fibers

In addition to damage mechanisms at the air-to-glass interface, optical fibers also display power handling limitations due to damage mechanisms within the optical fiber itself. Two categories of damage within the fiber are damage from bend losses and damage from photodarkening.

**Bend Losses**

Bend losses occur when a fiber is bent to a point where light traveling in the core is incident on the core/cladding interface at an angle higher than the critical angle, making total internal reflection impossible.Under these circumstances, light escapes the fiber, often in one localized area. The light escaping the fiber typically has a high power density, which can cause burns to the fiber as well as any surrounding furcation tubing.

A special category of optical fiber, called double-clad fiber, can reduce the risk of bend-loss damage by allowing the fiber's cladding (2nd layer) to also function as a waveguide in addition to the core. By making the critical angle of the cladding/coating interface higher than the critical angle of the core/clad interface, light that escapes the core is loosely confined within the cladding. It will then leak out over a distance of centimeters or meters instead of at one localized spot within the fiber, minimizing damage. Thorlabs manufactures and sells 0.22 NA double-clad multimode fiber, which boasts very high, megawatt range power handling.

**Photodarkening**

A second damage mechanism within optical fiber, called photodarkening or solarization, typically occurs over time in fibers used with ultraviolet or short-wavelength visible light. The pure silica core of standard multimode optical fiber can transmit ultraviolet light, but the attenuation at these short wavelengths increases with the time exposed to the light. The mechanism that causes photodarkening is largely unknown, but several strategies have been developed to combat it. Fibers with a very low hydroxyl ion (OH) content have been found to resist photodarkening. Other dopants, including fluorine, can also reduce photodarkening.

Germanium-doped silica, which is commonly used for the core of single mode fiber for red or IR wavelengths, can experience photodarkening with blue visible light. Thus, pure silica core single mode fibers are typically used with short wavelength visible light. Single mode fibers are typically not used with UV light due to the small MFD at these wavelengths, which makes coupling extremely difficult.

Even with the above strategies in place, all fibers eventually experience photodarkening when used with UV light, and thus, fibers used with these wavelengths should be considered consumables.

## Tips for Maximizing an Optical Fiber's Power Handling Capability

With a clear understanding of the power-limiting mechanisms of an optical fiber, strategies can be implemented to increase a fiber's power handling capability and reduce the risk of damage in a given application. All of the calculations above only apply if the following strategies are implemented.

One of the most important aspects of a fiber's power-handling capability is the quality of the end face. The end face should be clean and clear of dirt and other contaminants that can cause scattering of coupled light. Additionally, if working with bare fiber, the end of the fiber should have a good quality cleave, and any splices should be of good quality to prevent scattering at interfaces.

The alignment process for coupling light into optical fiber is also important to avoid damage to the fiber. During alignment, before optimum coupling is achieved, light may be easily focused onto parts of the fiber other than the core. If a high power beam is focused on the cladding or other parts of the fiber, scattering can occur, causing damage.

Additionally, terminated fibers should not be plugged in or unplugged while the light source is on, again so that focused beams of light are not incident on fragile parts of the connector, possibly causing damage.

Bend losses, discussed above, can cause localized burning in an optical fiber when a large amount of light escapes the fiber in a small area. Fibers carrying large amounts of light should be secured to a steady surface along their entire length to avoid being disturbed or bent.

Additionally, choosing an appropriate optical fiber for a given application can help to avoid damage. Large-mode-area fibers are a good alternative to standard single mode fibers in high-power applications. They provide good beam quality with a larger MFD, thereby decreasing power densities. Standard single mode fibers are also not generally used for ultraviolet applications or high-peak-power pulsed applications due to the high spatial power densities these applications present.

## Rotary Joint Patch Cables with Ø200 µm Fiber

| Item # | Fiber | Core Diameter | Cladding Diameter | NA | Bend Radius (Short Term/Long Term) | Wavelength Range | Attenuation Plot | Connectors | Jacket |
|---|---|---|---|---|---|---|---|---|---|
| RJPS2 | FT200EMT | 200 ± 5 µm | 225 ± 5 µm | 0.39 | 9 mm / 18 mm | 400 - 2200 nm (Low OH) | | SMA905 (10230A[a]) | FT020 (Ø2 mm) |
| RJPF2 | | | | | | | | FC/PC (30230C1[b]) | |

- Connectorized with the 190088CP strain relief boot for Ø2 mm tubing
- Connectorized with the 190066CP strain relief boot for Ø2 mm tubing

| Part Number | Description | Price | Availability |
|---|---|---|---|
| RJPS2 | SMA to SMA, Ø200 µm, 0.39 NA, Rotating Patch Cable, 2 m Long | $316.00 | Today |
| RJPF2 | FC/PC to FC/PC, Ø200 µm, 0.39 NA, Rotating Patch Cable, 2 m Long | $316.00 | 3-5 Days |

## Rotary Joint Patch Cables with Ø400 µm Fiber

| Item # | Fiber | Core Diameter | Cladding Diameter | NA | Bend Radius (Short Term/Long Term) | Wavelength Range | Attenuation Plot | Connectors | Jacket |
|---|---|---|---|---|---|---|---|---|---|
| RJPS4 | FT400EMT | 400 ± 8 µm | 425 ± 10 µm | 0.39 | 20 mm / 40 mm | 400 - 2200 nm (Low OH) | | SMA905 (10440A[a]) | FT020 (Ø2 mm) |
| RJPF4 | | | | | | | | FC/PC (30440C1[b]) | |

- Connectorized with the 190088CP strain relief boot for Ø2 mm tubing
- Connectorized with the 190066CP strain relief boot for Ø2 mm tubing

| Part Number | Description | Price | Availability |
|---|---|---|---|
| RJPS4 | SMA to SMA, Ø400 µm, 0.39 NA, Rotating Patch Cable, 2 m Long | $342.00 | Today |
| RJPF4 | FC/PC to FC/PC, Ø400 µm, 0.39 NA, Rotating Patch Cable, 2 m Long | $342.00 | Today |

Visit the *Multimode Fiber Optic Rotary Joint Patch Cables* page for pricing and availability information:
https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=7556